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EFFECTS OF OPERATIONAL STRATEGIES ON PERFORMANCE AND COSTS OF ELECTRIC ENERGY STORAGE SYSTEMS

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Abstract

An important technical issue of electric energy storage systems (EESSs) is the operational strategy (OS). It strongly influences performance, costs and therefore profitability of the systems and is still insufficiently discussed. This paper investigates the influences of different types of OS on performance and costs of EESSs, using the example of a residential building with photovoltaic installation (PV) and a small combined heat and power plant (CHP). The function of the EESS is on the one hand to increase the self-consumption of the building and on the other hand to reduce the peaks and volatility of the feed-in caused by the PV and CHP systems, which are conflicting goals. To reach those goals, four levels of OS are defined. For each level a control system is designed and analyzed for an exemplary building.

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Keywords: Electric energy storage system, operational strategy, control system, apartment building, self-consumption, grid service

1. Introduction

Along with the increase of renewable energies in the power grid, there is a rising demand for storage capacities [1]. Even for small households with PV an electric energy storage system (EESS) can be profitable by increasing the self-consumption of the building. With a higher penetration of renewable

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energies in the power grid EESSs will be necessary to provide valuable grid services in addition to their main task [2]-[3]. A necessary part of every EESS is its operational strategy (OS). It determines the EESS length of charging and discharging cycles and the corresponding electrical power. It therefore strongly influences the performance, the costs and the profitability of the system [4]-[5]. Depending on the complexity of the control system, different levels of OS can be distinguished. The levels strongly influence performance and costs of EESS. Using the example of a residential apartment building with photovoltaic installation (PV) and a small combined heat and power plant (CHP), these interdependencies are shown in this paper. Figure 1 shows the power demand of the building, the production of PV and CHP and the residual load for 14 days in February without an EESS. The load profile was measured in a real building and has a resolution of one value per minute. The production systems are dimensioned in a way that the building can produce most of its energy demand itself over the year. The production profiles of the PV and CHP system are synthetically generated from radiation data measured in Germany. The residual load can be calculated by the difference of power demand and total production. Thus a positive residual load is an energy demand and a negative residual load stands for a feed-in.

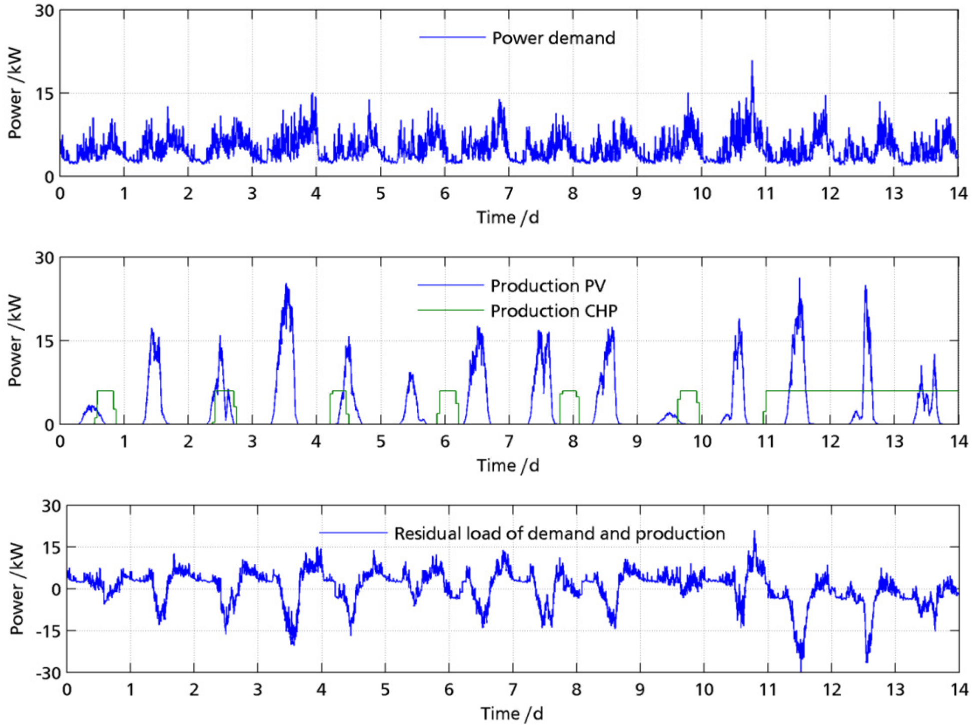

Fig. 1. Components of the load profile of the apartment building

In the described building a Li-ion battery as EESS is installed. In order to reach a high degree of autarky, the dimensions of the EESS are chosen to 56 kWh of usable capacity and a nominal power of 20 kW for charging and discharging. The efficiency of the system is estimated to a one-way conversion efficiency of 0.9, no self-discharge losses and a permanent power demand of the peripheral equipment of 0.3 kW. The function of the EESS is on the one hand to increase the use of self-produced energy in the building. On the other hand the EESS has to reduce the peaks and volatility of the feed-in caused by the

PV and CHP systems in order to contribute to high grid stability. The scenario investigated does not involve any other changes in the electricity production or consumption of the building. This means that no demand side management systems or additional intelligence of the CHP are considered. The CHP is only operated according to the heat demand of the building. This paper aims to show the influence of different levels of OS on performance and cost of the EESS and is structured as follows. In chapter 2 the dynamic simulation model, the different levels of OS as well as performance indicators are defined. In chapter 3 results are presented for the different levels of OS. The paper ends with a discussion of the results and a conclusion.

2. Description of the Model and Performance Indicators

The EESS is modeled with a block diagram shown in Figure 2. The conversion losses, the self-discharge losses and the consumption of the peripheral equipment are implemented into the loss block. The state of charge (SoC) of the EESS is calculated by normalizing the actual stored physical energy by the total usable capacity.

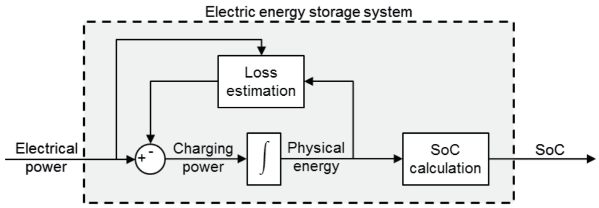

Fig. 2. Model of the electric energy storage system

The operational strategy is implemented in form of a cascaded feedback controller, with an inner power controller and an outer SoC controller, see Figure 3. The inner power controller feeds back the power at the network connection point (grid). In terms of the power controller the load of the building and the power production systems PV and CHP act as a disturbance on the electricity grid. The feed-forward input of the power controller allows for a variable setpoint of the power controller depending on the prediction. The prediction is performed based on internal information (time and date and information about the load, CHP and PV) and external information (weather forecast). For the calculation of the prediction perfect forecast data is used, meaning that prediction errors are not considered in this investigation. In order to control the cycles and dynamics of the EESS a filter in the feedback of the residual load is used. For the used Li-ion battery a filter time constant of 1 hour was chosen.

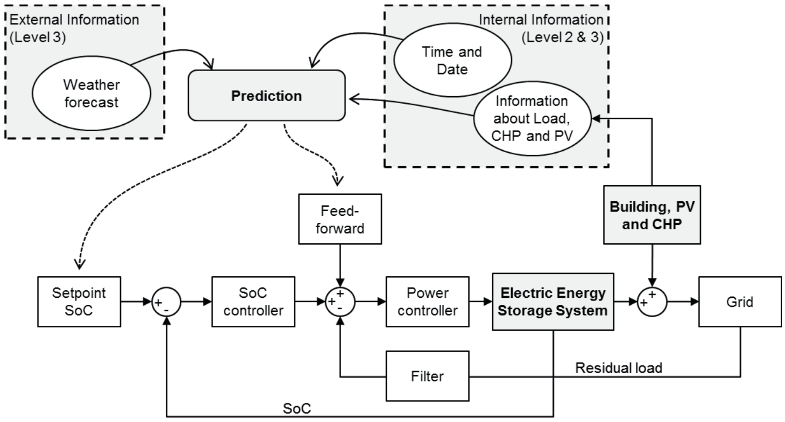

Fig. 3. Model of the electric energy storage system

The basic structure of the cascaded feedback controller is used for all four levels of operational strategies discussed in this paper. The levels differ in the way this structure is parameterized, but not in the structure itself. Table 1 shows the used parameters for the different investigated levels for the operational strategies. In level 0 a static parameter is used for the power controller, whereas in level 1 a non-linear SoC controller is configured. In case of level 2 and 3 a feed-forward-input of the power controller based on the prediction and a time-variable setpoint of the SoC controller are added.

Table 1: Components of the control system on different levels of the OS

Operational strategy level	Parameterization of the control system
0	Linear power controller with feed-forward set to zero, SoC controller parameters set to zero
1	Linear power controller with feed-forward set to zero, non-linear SoC controller with constant setpoint
2	Linear power controller with feed-forward based on prediction using building internal information, SoC controller with time-variable set point
3	Linear power controller with feed-forward based on prediction using building internal information and external weather forecast, SoC controller with time-variable set point

For the assessment of different levels of operational strategies, the following five performance indicators are used:

The self-consumption ratio (SCR) is defined by the quotient of the amount of self-produced and self-consumed electrical energy $\mathrm{E_{prod,used}}$ and the total amount of self-produced electrical energy $\mathrm{E_{prod}}$:

$$SCR = \frac{E_{prod,used}}{E_{prod}}.$$

In contrast to the SCR the self-supply ratio (SSR) is defined by the quotient of the amount of self-produced and self-consumed electrical energy $E_{prod,used}$ and the total amount of self-consumed electrical energy E_{con}:

$$SSR = \frac{E_{prod,used}}{E_{con}}.$$

The peak reduction ratio (PRR) describes the second goal of the EESS. It is defined as the PV feed-in peak without EESS P_{peak} minus the PV feed-in peak with EESS $P_{peak,EESS}$ divided by the PV feed-in peak without EESS P_{peak}:

$$PRR = \frac{P_{peak} - P_{peak,EESS}}{P_{peak}}.$$

The loss ratio (LR) is defined by the quotient of the total losses of the EESS during the sample period E_{loss} and the total amount of self-produced electrical energy E_{prod}:

$$LR = \frac{E_{loss}}{E_{prod}}.$$

The number of cycles (NC) is defined by the theoretical number of full charging and discharging cycles when combining the partial charging and discharging cycles observed during the sample period.

3. Results

Different OSs are applied to the EESS installed in the building and the load profile is simulated for 14 days with the described model. The performance indicators are calculated for this period and relevant days are graphically analyzed in this part of the paper. In order to evaluate the building before installing the EESS the performance indicators have to be calculated without EESS (see Table 2). The self-consumption ratio without EESS amounts to 51.1%. The self-supply ratio is 49.3% which means that almost half of the electricity demand is satisfied by self-production.

Table 2: Performance indicators without EESS

Self-consumption ratio	Self-supply ratio	Peak reduction ratio	Loss ratio	Number of cycles
51.1%	49.3%	0%	0%	0

3.1. Level 0 Operational Strategy

The power controller charges the EESS whenever the residual load of the building is below zero that is the building is feeding-in. As can be seen in Figure 4 this behavior leads to a rapid rise of the state of charge of the EESS on days with intensive sun (for example day 4) resulting in a fully charged EESS and an abrupt increase of the feed-in around 2 p.m. (see Figure 4).

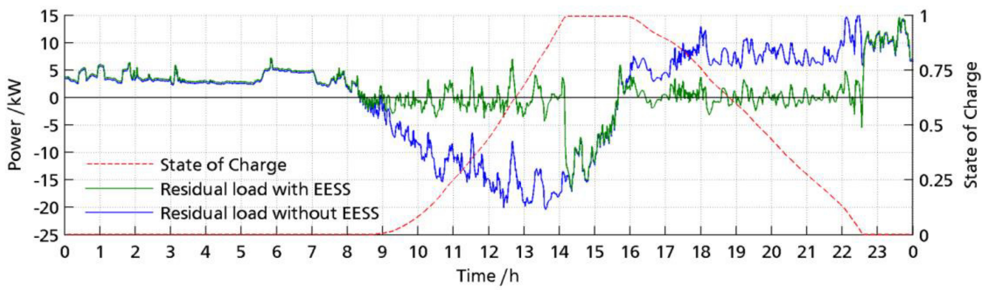

Fig. 4. Day 4 OS level 0

Another problem that arises on days with a high CHP runtime with such a control strategy is that the EESS is already partly charged when PV production becomes dominant in the load curve (see Figure 5). Since the CHP lowers the residual load of the building below zero during the night, the EESS charges with the difference between residual load and the zero line. On day 12, this behavior leads to a state of charge of 0.5 at around 10 a.m. Therefore, the available capacity of the EESS to reduce the feed-in peak of the PV system is reduced resulting in a fully charged EESS before noon. Thus a peak reduction is not possible anymore. Due to the constant feed-in of the CHP the residual load of the building is near zero in the evening which prevents the EESS from discharging. This leads to a high SoC on the next day and thus to a lower storage capacity.

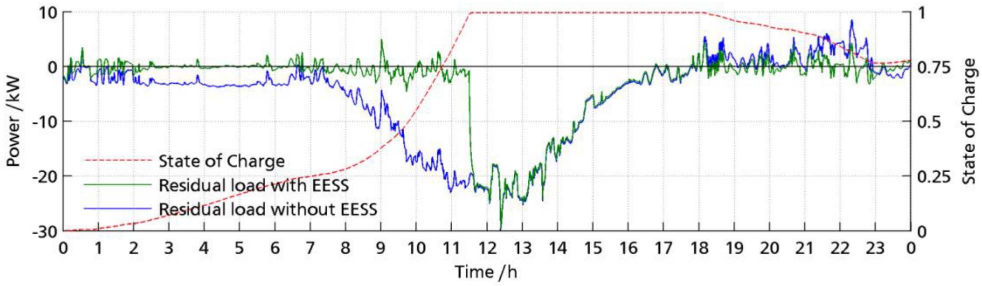

Fig. 5. Day 12 OS level 0

Table 3 shows the numerical results for the full two week profile. As can be seen from the SCR and the SSR, the EESS with an OS of level 0 reaches a high degree of autarky of the building. The feed-in peaks, however, could not be reduced significantly (PRR = 1%). The results show that with a level 0 control strategy only one goal at the same time, in this case a high self-consumption ratio, can be achieved. The losses of the EESS correspond to a dissipation of about 12% of the produced electrical energy. The number of charge and discharge cycles is typical for a chemical EESS and allows a long lifetime.

Table 3: Results with EESS and a level 0 OS

Self-consumption ratio	Self-supply ratio	Peak reduction ratio	Loss ratio	Number of cycles
81.3%	62.4%	1.0%	11.7%	6.0

3.2. Level 1 Operational Strategy

The level 1 OS consists of an additional SoC controller with constant setpoint to prevent the EESS from charging to fast early in the day. The result for day 4 shows Figure 6. As can be seen the SoC only increases slowly which leads to more available storage capacity around noon. Therefore the EESS can reduce the feed-in peak. The constant setpoint of the SoC controller, however, also leads to an inefficient use of the EESS (maximum SoC smaller than 0.75) and a rapid discharging into the grid in the evening (residual load below 0 after 4 p.m.). Stored energy that is fed into the grid, however, does not contribute to the SSR.

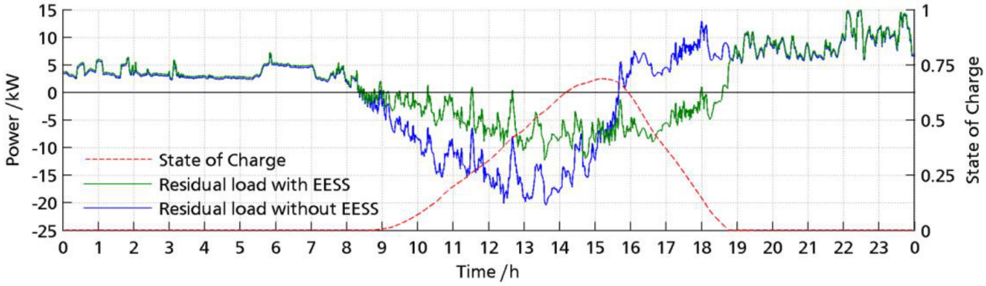

Fig. 6. Day 4 OS level 1

Figure 7 shows day 12. Compared to day 4 the capacity of the EESS is fully used (SoC = 1) but the rapid discharge into the grid during the evening hours remains.

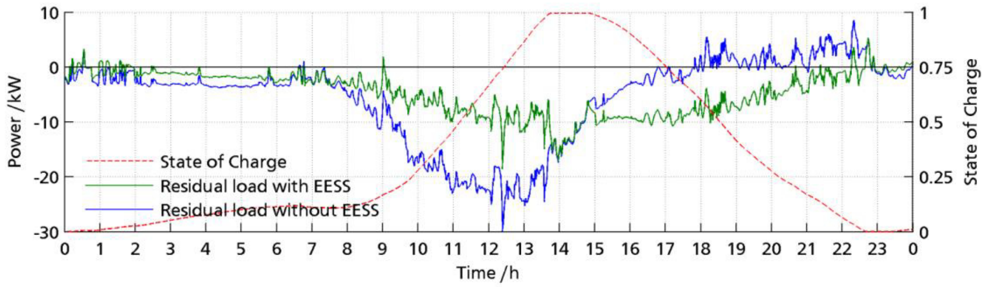

Fig. 7. Day 12 OS level 1

Comparing the results with the previous strategy one observes a much higher peak-reduction ratio of 38% compared to 1% before (see Table 4). But this increase in PRR leads to a lower SCR and SSR because the full capacity of the EESS is less frequently used (e.g. on day 4). This also leads to a lower loss ratio and numbers of cycles.

Table 4: Results with EESS and a level 1 OS

Self-consumption ratio	Self-supply ratio	Peak reduction ratio	Loss ratio	Number of cycles
74.1%	53.3%	38.0%	10.6%	5.2

3.3. Level 2 Operational Strategy

The results can be improved using a prediction method based on internal information, in this case date and time and the state of the CHP. Through a time-variable set point of the SoC controller the charging and discharging behavior of the EESS is enhanced. Overnight the EESS now tries to discharge constantly whereas during the course of the day the charging rate slowly increases. The result for day 4 can be seen in Figure 8. Compared to the level 1 OS the storage capacity is almost completely used and the discharging process is rather constant.

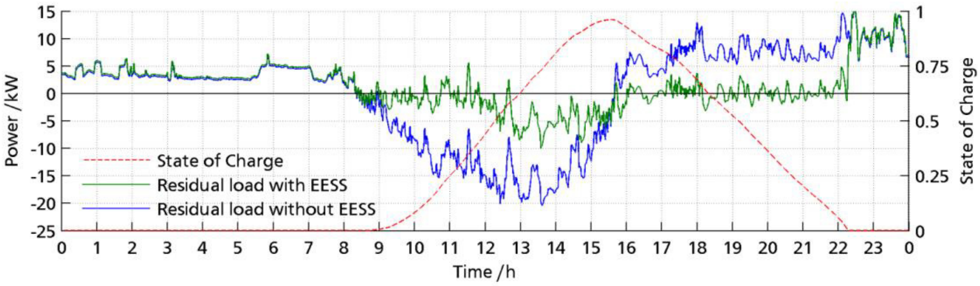

Fig. 8. Day 4 OS level 2

Even on day 12 (see Figure 9) the EESS reaches its maximum SoC only for a short period of time.

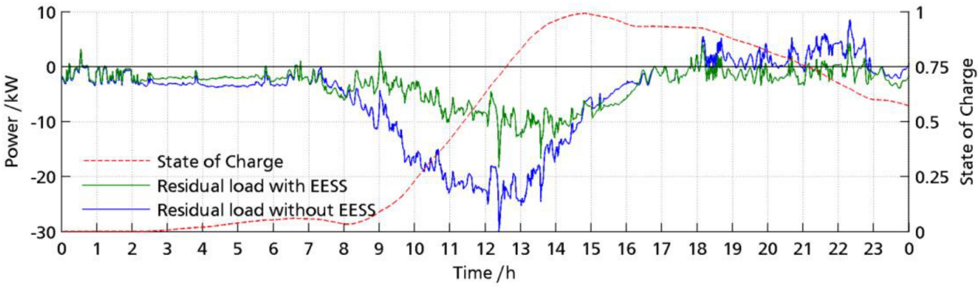

Fig. 9. Day 12 OS level 2

The numerical results draw the same pictures as the plots. The SCR and SSR could be significantly improved while keeping the PRR approximately constant (see Table 5). This OS dominates the lower OS levels (level 0 and 1) because the positive performance indicators increase and no trade-off is necessary. Compared to the results of the level 0 OS the performance indicators SCR and SSR are equal while a PRR of 39 % is achieved by similar losses of the EESS.

Table 5: Results with EESS and a level 2 OS

Self-consumption ratio	Self-supply ratio	Peak reduction ratio	Loss ratio	Number of cycles
82.8%	61.2%	38.9%	12.1%	6.7

3.4. Level 3 Operational Strategy

In level 2 only internal information is used for the prediction while in level 3 the prediction system is extended by external information such as weather forecasts. The sun forecast is used to determine the optimal point to start charging in the morning without reaching the storage limit too early. The temperature forecast is used to predict whether the CHP system is going to produce electricity during the day. Figure 10 and Figure 11 show the results. On day 4 the residual load with EESS reaches an even straighter trend in the afternoon than the level 2 OS.

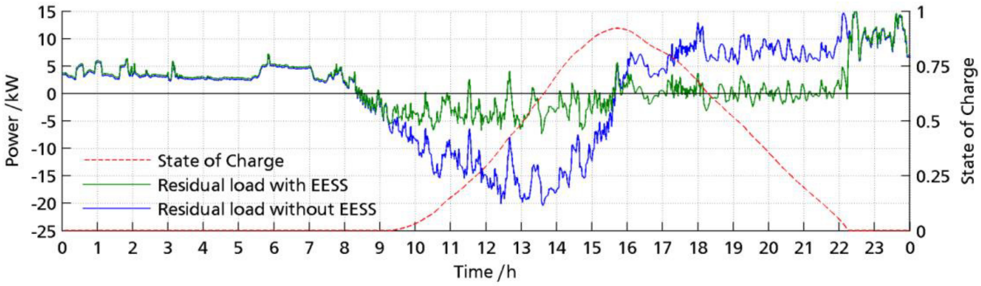

Fig. 10. Day 4 OS level 3

On day 12 the effect of the forecast can be observed even better. With the level 2 OS the EESS was not able to charge in the afternoon resulting in an unstable load curve. Also in the early morning hours the EESS shows a better performance, since the rather constant feed-in of the CHP does not charge the EESS. This leads to a higher available storage capacity to reduce the feed-in peak around noon.

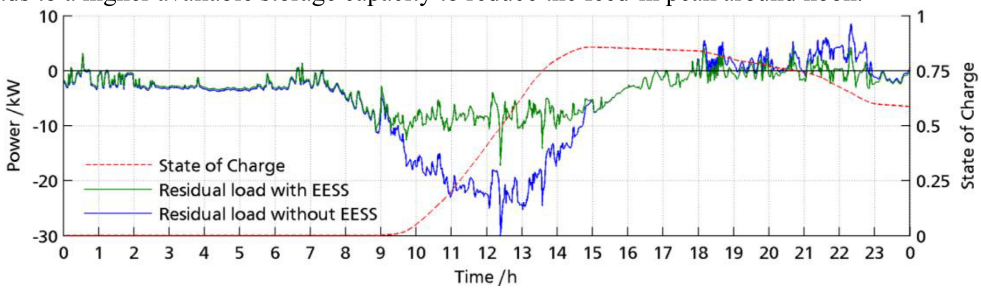

Fig. 11. Day 12 OS level 3

Compared to the level 2 OS the performance of the EESS could be further improved. Both performance indicators SSR and PRR are increased. The decrease of the SCR can be explained by the lower LR. The NC remains similar.

Table 6: Results with EESS and a level 3 OS

Self-consumption ratio	Self-supply ratio	Peak reduction ratio	Loss ratio	Number of cycles
80.9%	62.5%	42.5%	11.9%	6.8

3.5. Level 3 Operational Strategy with reduced storage capacity

While achieving high performance indicators using level 3 OS, the capacity of the EESS is not efficiently utilized. This allows for a reduction of the capacity leading to lower initial system costs. For the following investigations an EESS with 44 kWh is used, which is a reduction of 21 %. The nominal power remains at 20 kW, Table 7 gives the results.

Table 7: Results with EESS and a level 3 OS

Self-consumption ratio	Self-supply ratio	Peak reduction ratio	Loss ratio	Number of cycles
79.1%	61.9%	37%	11.6%	8.1

Compared to the previous results the SCR slightly decreases by 1.8% while the SSR drops by 0.6 %. The PRR is reduced by 5.5 %, because OS takes the smaller capacity into account, leading to a higher constant feed-in during the day. As can be seen from the results PRR and storage capacity are strongly interrelated.

4. Discussion and Conclusion

The suggested approach for the implementation of operational strategies into energy storage systems considers the subject as a problem to be solved by control theory. The cascaded approach considers a power controller, allowing for the control of the power flow of the EESS. The overlaying SoC controller allows for the control of its state of charge. The four discussed levels of operational strategies differ in the amount and kind of information the prediction method uses to parameterize the cascaded control system.

While the simple level 0 operational strategy does not use the SoC controller, it allows for a very high self-supply. The peak reduction resulting from the implementation of such an OS equals zero. Level 1 OS uses the SoC controller and allows a trade-off between peak reduction and self-supply. The results show the high potential of the level 2 and level 3 operational strategies, which take prediction methods into account to increase the performance of the EESS. Such strategies allow for both, a high peak reduction in combination with a high self-supply. Level 2 OSs use internal data for the prediction methods like the date and time as well as the current status of the energy generating and absorbing units. Level 3 operational strategies use external information such as weather forecasts. On the one hand the level 3 OSs are more complex and more error-prone caused by the use of external information. On the other hand the achieved utilization of the EESS with level 3 operational strategy allows reducing the capacity of the EESS of 21 % while gaining a similar performance of the system. This is a very important result, since it allows for approx. 20 % lower investment costs of the system. An intelligent control strategy does not only improve the EESS in terms of performance but also enables high cost reductions through smaller storage capacities.While the presented approach is based on heuristic tuning of the control parameters, optimal control and robust control methods should be used in the next steps to further increase the performance of the EESS. Also the used assessment criteria should be further discussed. For example the precision of the power output of the EESS might be a relevant criterion to determine the quality of the EESS. Moreover the results should be verified for different building configurations and longer time periods (e.g. a full year).

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